Accepted by *The Astrophysical Journal Letters*.

The Very Extended Ionized Nebula around the Quasar MR2251-178

P. L. Shopbell, S. Veilleux[1]
Department of Astronomy, University of Maryland, College Park, MD 20742;
pls,veilleux@astro.umd.edu

and

J. Bland-Hawthorn
Anglo-Australian Observatory, P.O. Box 296, Epping, NSW 2121, Australia;
jbh@aaoepp2.aao.gov.au

ABSTRACT

We report the results of deep Hα imaging of the ionized gas surrounding the low-redshift ($z = 0.0638$) quasar MR 2251–178 using the TAURUS Tunable Filter (TTF) on the Anglo-Australian Telescope. Our observations reach a 2-σ detection level of $\sim 5 \times 10^{-18}$ erg s^{-1} cm^{-2} arcsec^{-2}, more than an order of magnitude deeper than conventional narrowband images previously published on this object. Our data reveal a spiral complex that extends more or less symmetrically over $\sim$ 200 kpc, making it the largest known quasar nebula. The total mass of ionized gas is 6×10^{10} M$_\odot$ (upper limit), a large fraction of which is in a very faint, diffuse component. The large and symmetric extent of the gaseous envelope favors a model in which the filamentary and diffuse emission arises from a large cloud complex, photoionized by the bright quasar. A crude kinematic analysis reveals relatively smooth rotation, suggesting that the envelope did not originate with a cooling flow, a past merger event, or an interaction with the nearby galaxy G1.

Subject headings: quasars: individual (MR 2251–178); galaxies: halos; quasars: general; intergalactic medium; instrumentation: spectrographs

1. Introduction

In the ongoing quest to better understand the luminous quasar population, one of the most fertile areas of study has been the investigation of their galaxy environments. The host galaxy not

[1]Cottrell Scholar of the Research Corporation

only must provide fueling for the central engine, but should also display the effects of the strong nuclear ionizing emission and the impact of dynamic activity, such as jets and winds.

Broadband observations of quasar environments suggest a surprising variety of host galaxy morphologies, including spirals and ellipticals, nearby companions, and tidal interactions. While early ground-based work indicated a large percentage of spirals amongst low-redshift quasar hosts ($\gtrsim$ 40%; Hutchings *et al.* 1984a) and no concrete evidence for ellipticals, subsequent HST observations find an elliptical fraction of greater than half (Bahcall *et al.* 1997). More recent HST work suggests in fact that nearly all radio-loud and radio-quiet quasars reside in massive ellipticals (McLure *et al.* 1999; see also Disney *et al.* 1995). A substantial fraction of quasar host galaxies exhibit tidal tails and streamers indicative of interactions (e.g., Hutchings & Campbell 1983; Hutchings *et al.* 1984b; Stockton & MacKenty 1987; Bahcall *et al.* 1997; Hutchings *et al.* 1999). Evidence for extended gas from interactions has also been found at H I 21 cm (e.g., Lim & Ho 1999). The presence of companion galaxies is common; the QSO/galaxy correlation function is evidently several times that for galaxies alone (Fisher *et al.* 1996).

Given the strong line emission in the nuclei of active galaxies and quasars, as well as the prevalence of ionized gas in interacting systems, narrowband observations of quasar environments have proved interesting as well. The imaging survey of Stockton & MacKenty (1987), the largest to date, found highly-structured [O III] emission in a quarter of 47 luminous QSOs, with typical extents of a few tens of kpc. Similar spectroscopic observations have detected extended regions of line emission in half of the objects observed (Boroson *et al.* 1985). The line ratios usually suggest photoionization by the nuclear power-law spectrum (e.g., Boroson *et al.* 1985; Boisson *et al.* 1994), although stellar absorption lines from (presumably in-situ) stars are sometimes seen (e.g., Miller *et al.* 1996). Kinematic studies of the ionized gas component are scarce, but the gas motions generally appear to be complex and chaotic (e.g., Durret *et al.* 1994). The size and luminosity of the ionized component appear to be correlated with both the narrow-line nuclear luminosity and the radio power of the quasar (Boroson *et al.* 1985; Stockton & MacKenty 1987; Véron-Cetty & Woltjer 1990).

The quasar MR 2251–178 is one of a few radio-quiet quasars which exhibit an extended gaseous envelope (e.g., Bergeron *et al.* 1983). This quasar was first discovered as a strong and variable X-ray source by the *Ariel V* satellite (Cooke *et al.* 1978). Subsequent observations identified the object as a quasar at a redshift of 0.0638 ± 0.0015 (Ricker *et al.* 1978; Canizares *et al.* 1978), residing in the outskirts of a small cluster (Phillips 1980). In this *Letter*, we present deep Hα observations of MR 2251–178 obtained with the TAURUS Tunable Filter (TTF), a new, etalon-based instrument which has been optimized for the detection of faint, extended emission-line gas. These new data allow us to better constrain the extent, velocity field, and origin of the ionized nebula around MR 2251–178.

2. Observations and Reductions

MR 2251–178 was observed on August 30, 1998 using the TTF at the f/8 Cassegrain focus of the 3.9-meter AAT. The TTF instrument consists of a pair of modified high-finesse ($N \sim 40$) Queensgate etalons (blue and red) which can be tuned to provide narrowband imaging anywhere within the wavelength range 400 to 960 nm, through an arbitrary bandpass, with resolving powers of 100 to 1000.[2] The observations of MR 2251–178 were made with the red side of the TTF, using a mediumband ($\Delta\lambda = 26.0$ nm) blocking filter centered at 707 nm, tilted by 16°. Two 600-second exposures were obtained at each of two etalon spacings. The exposures were dithered amongst pointings on a 15″ grid. The average atmospheric seeing of 1.3″ was oversampled by the 0.37″ pixels. The night was photometric. MR 2251–178 was also observed on September 3, 1998 in direct imaging mode, using a standard I-band filter.

Fits to a number of emission lines from observations of a calibration lamp (CuAr) were used to determine the relationship between wavelength, spatial position, and etalon gap spacing. The free spectral range of the etalon, i.e., the distance between orders, was found to be 265.8 Å, well-matched to the bandwidth of the blocking filter. The system was used in the 26th order of interference, with a 9 micron etalon gap, at an effective finesse of 39.7. This translates to a spectral resolution of 6.8 Å, or $R \sim 1040$, with an effective bandpass of ~ 12 Å. The pair of etalon spacings produced imagery with central wavelengths on the optical axis of 6983 Å and 6986 Å, corresponding to redshifted velocities of 60 and 195 km s^{-1} relative to the quasar. The field is essentially monochromatic: pixels $\sim 1'$ from the optical axis have a central wavelength only 1.3 Å (60 km s^{-1}) bluer than pixels on-axis. The optical axis is located approximately 35″ northwest of the quasar.

The data frames were bias-subtracted and flatfielded in the typical manner. An azimuthally-symmetric sky frame was produced from a mean radial sky spectrum for each image and subsequently subtracted. Images at each of the two etalon spacings were then aligned and combined using 9 stellar objects in the field. An image mask was used to simultaneously remove three ghost reflections from each image. The data were flux calibrated using observations of the standard star EG 21 (Stone & Baldwin 1983).

The I-band observations were reduced following standard CCD procedures. The summed continuum image was matched to the narrowband imagery using a number of stars and subsequently subtracted. A few remaining stellar residuals and cosmetic defects were identified and repaired by hand.

---

[2]Consult Bland-Hawthorn & Jones (1998) and the TTF web page (`http://www.aao.gov.au/local/www/jbh/ttf/`) for further details.

3. Discussion

Figure 1 presents our final Hα images of MR 2251–178 at each of the two etalon spacings (panels *a* and *b*), as well as the I-band continuum image (panel *c*) and a combined Hα image (panel *d*). The 2-σ detection limit of the Hα images is $\sim 5 \times 10^{-18}$ erg s^{-1} cm^{-2} arcsec^{-2}, more than an order of magnitude fainter than previously published data on this object. In the discussion that follows, we assume $H_0 = 50$ km s^{-1} Mpc^{-1} and a corresponding image scale of 1.9 kpc arcsec^{-1}.

3.1. Morphology

Published optical imagery and spectroscopy have detected two ionized gas components around the quasar MR 2251–178: an elongated, highly-ionized circumnuclear component of diameter ~ 27 kpc, and an extended envelope of faint Hα- and [O III]-emitting filaments out to a radius of ~ 110 kpc (Bergeron *et al.* 1983; Hansen *et al.* 1984; Alighieri *et al.* 1984; Macchetto *et al.* 1990). Our observations confirm these findings and reveal a number of new features.

The circumnuclear component of ionized gas is evidenced by strong Hα emission directly surrounding the quasar, extending out to a radius of ~ 20 kpc. This emission is slightly elongated in the east-west direction, i.e., along the axis of the quasar's radio jet ($PA \sim 102°$; Macchetto *et al.* 1990), and has been identified as an "extended emission-line region" (EELR) of the quasar host galaxy (Mulder & Valentijn 1992). As others have reported on characteristics of the EELR in some detail, we will say nothing more of it herein.

The extended ionized gas component is observed as a much larger network of diffuse and filamentary emission exterior to the EELR. Above a flux level of 1.8×10^{-17} erg s^{-1} cm^{-2} arcsec^{-2}, diffuse Hα emission is visible surrounding the galaxy to a radius of at least 50 kpc. Knots and filaments of ionized gas are visible to radii up to 120 kpc towards the northeast, southeast, and southwest. The filaments display a spiral morphology and exhibit a remarkable azimuthal symmetry that has not been previously seen. The total extent of this complex ($\sim$ 200 kpc) makes it the largest known around a quasar. We derive a total flux from the extended ionized gas component of 1.4×10^{-13} erg s^{-1} cm^{-2}, or a luminosity of 2.5×10^{42} erg s^{-1} at the redshift distance of the quasar (384 Mpc). This value, as well as the corresponding upper limit on the gas mass of 6×10^{10} M$_\odot$, is comparable or slightly greater than previously published results (e.g., Nørgaard-Nielsen *et al.* 1986; Macchetto *et al.* 1990).

A few of the individual knots and filaments have been previously noted; these are indicated in Figure 1*d*, using the denotations from Macchetto *et al.* (1990). Several additional knots also noted by these authors and others (e.g., Alighieri *et al.* 1984) are conspicuous in their absence from our imagery. Most notable among these are the "E" knots interior to the eastern filament in Figure 1. As will be noted in the following section, this absence is probably due to the large range of velocity spanned by the filament emission, relative to our narrow bandpasses.

3.2. Kinematics

The spectroscopy which initially discovered the extended ionized component of MR 2251–178 also provided the first kinematical information on the nebula (Bergeron *et al.* 1983). Those observations revealed a normal rotation curve along each of three position angles, with peak velocities of ~ 150 km s^{-1}. Surprisingly, the extended nebula appears to be rotating in an opposite sense to the inner (EELR) regions of the galaxy (e.g., Nørgaard-Nielsen *et al.* 1986). The only published two-dimensional kinematics of the system are narrow-field Hα Fabry-Perot observations of the EELR (Mulder & Valentijn 1992).

Comparison of our Hα imagery at each of the two distinct etalon positions reveals a broad velocity gradient across the quasar nebula. The maximum gradient appears to be along a position angle of $\sim 40^{\circ}$, with the eastern filaments generally less redshifted than the western filaments.

The eastern filaments are clearly detected in both the "blue" and "red" images. Since an upper limit of ~ 200 km s^{-1} has been measured for their line widths (Bergeron *et al.* 1983), the central velocity of these filaments must lie within the overlap region of our two velocity regimes. Accounting for its distance from the optical axis, the ionized gas east of the quasar must be near the systemic velocity of the quasar.

The western filaments are detected only in the "red" image and appear to be redshifted from the systemic velocity by a value of $\sim 200 - 300$ km s^{-1}. This correlates well with the imaging observations of Macchetto *et al.* (1990), whose broad ($\Delta\lambda = 64$ Å) Hα filter barely detected the western filaments out to a velocity of ~ 200 km s^{-1} relative to the quasar. Furthermore, these authors more readily detected the western filaments in their [O III] imagery, which encompassed a redder range of velocities.

We therefore confirm that the velocity structure of the extended ionized gas component does not appear to follow the rotation curve of the quasar (Nørgaard-Nielsen *et al.* 1986; Mulder & Valentijn 1992). The broad velocity range of our images and the limitation of two distinct velocity samples restricts us from analyzing more precise velocity variations, e.g., amongst individual knots and filaments.

3.3. The Origin of the H II Envelope

Several scenarios have been put forth for the origin of the ionized gas envelope in MR 2251–178, including tidal debris from an interaction with galaxy G1 some $\sim 2 \times 10^{8}$ years ago, similar debris from a merging event, clouds expelled from the quasar and/or host galaxy, a cooling flow, or the ionized portion of a large H I envelope that is gravitationally bound to the quasar (e.g., Nørgaard-Nielsen *et al.* 1986; Macchetto *et al.* 1990). Our observations reveal a tremendous spatial extent for the emission in this system. We also observe a relatively high degree of symmetry in the envelope, including at least two "arms" of ionized gas and a pervasive diffuse component. This

symmetry, together with the organized large-scale kinematics, casts doubt upon the interaction model for creation of the ionized gas. Furthermore, the galaxy G1, the usual culprit quoted as an interacting companion to MR 2251–178, has a velocity redshifted by 1246 km s^{-1} relative to the quasar (Bergeron *et al.* 1983), yet its spatial position corresponds to that of relatively blueshifted filaments. Published spectroscopy shows the emission lines from these filaments to be symmetric and significantly narrower than this (e.g., Bergeron *et al.* 1983), although we cannot rule out the presence of a very faint, high-velocity streamer extending out toward G1.

Nevertheless, the coarse kinematic structure of the extended ionized gas indicates that it represents a distinct component from the inner EELR region, since the latter appears to rotate in an opposite sense. This implies that the envelope most probably did not originate within the host galaxy of the quasar. A retrograde merging event, in which a small, gas-rich galaxy has been subsumed by the quasar, remains a possibility, however again the relatively well-ordered large-scale kinematics and azimuthal symmetry of the ionized envelope are problematic.

The cooling flow hypothesis appears equally unlikely. As pointed out by Macchetto *et al.* (1990), the large size and ordered kinematics of the envelope, and the off-centered position and peculiar systemic velocity of the quasar with respect to the underlying cluster, all argue against this scenario. By elimination, our observations therefore favor a model in which the extended ionized envelope resides within a large complex of H I gas centered about the quasar. If this is correct, a deep search for 21 cm H I line emission should reveal the massive neutral envelope and constrain its origin (e.g., captured intergalactic H I clouds, remnant accreting gas from galaxy formation, etc.).

3.4. The Ionization of the H II Envelope

The high excitation level of the brighter knots around MR 2251–178 (e.g., Bergeron *et al.* 1983; Nørgaard-Nielsen *et al.* 1986; Macchetto *et al.* 1990) requires an energetic source of ionization. In-situ ionization by a faint hot stellar component is unlikely to be dominant for a number of reasons. Deep broadband imagery of MR 2251–178 reveals a morphology very unlike that of our narrowband observations. The R-band image of Hutchings *et al.* (1999) exhibits a faint component extended along the N–S direction, markedly different from the symmetric spiral pattern that we observe in Hα. Moreover, Hutchings *et al.* (1999) do not detect an excess of continuum emission at the locations of any of the brighter Hα knots in the envelope. Perhaps even more damaging to the stellar ionization scenario is our detection of a large amount of diffuse ionized gas outside of the brighter knots. We therefore favor an external source of ionization.

The presence of a significant amount of ionized gas at large angles relative to the jet axis (PA $\sim 102°$; Macchetto *et al.* 1990) seems to rule out ionization mechanisms directly associated with the quasar jet (e.g., shocks). We are therefore left with the possibility that the ionization of the nebula is sustained by the quasar radiation field. As described in detail in previous studies (e.g.,

Bergeron *et al.* 1983; Nørgaard-Nielsen *et al.* 1986; Macchetto *et al.* 1990), the power radiated by the quasar can easily account for the high ionization level of the nebula. However, the relative symmetry of the envelope requires that the ionizing radiation is escaping the quasar symmetrically with respect to our line of sight. The large-scale radiation field from MR 2251–178 therefore shows no sign of anisotropy or alignment with the radio axis, contrary to expectations from unified models of active galactic nuclei that rely on orientation effects (e.g., Barthel 1989; Antonucci 1993; Urry & Padovani 1995). This symmetry of the radiation field, if typical of all quasars, may have important consequences on our understanding of the impact that quasars have on the intergalactic environment (e.g., proximity effect of Lyα clouds; Carswell *et al.* 1982; Murdoch *et al.* 1986).

4. Summary and Future Directions

Our deep Hα observations of MR 2251–178 reveal a spiral complex of ionized material that extends more or less symmetrically out to $\sim$ 120 kpc from the quasar. The coarse velocity field derived from our data shows a NE – SW velocity gradient that is opposite to that of the inner line-emitting region. The morphology and kinematics of the nebula cannot be easily explained by an interaction/merger event or a cooling flow. We favor the scenario in which the ionized material is part of a larger neutral envelope that is photoionized by the radiation field of the quasar. Deep H I 21-cm observations are needed to confirm this model.

We suspect that significant quantities of ionized gas may be present around luminous quasars, but have remained undetected with standard narrowband imaging techniques. The observations presented herein constitute only 40 minutes of integration, yet reach more than an order of magnitude deeper in flux than previous narrowband imagery. The TTF instrument allows the observer to tune the filter to a very precise bandpass in order to match the expected emission and avoid bright sky features. The TTF therefore promises to greatly impact a number of observational programs, such as those that aim at parameterizing ionized quasar envelopes and quantifying the impact of quasars on the intergalactic environment.

SV is grateful for support of this research by NSF/CAREER grant AST-9874973 and by a Cottrell Scholarship awarded by the Research Corporation.

REFERENCES

Alighieri, S. D. S., Perryman, M. A. C., & Macchetto, F. 1984, ApJ, 285, 567

Antonucci, R. 1993, ARA&A, 31, 473

Bahcall, J. N., Kirhakos, S., Saxe, D. H., & Schneider, D. P. 1997, ApJ, 479, 642

Barthel, P. D. 1989, ApJ, 336, 606

Bergeron, J., Boksenberg, A., Dennefeld, M., & Tarenghi, M. 1983, MNRAS, 202, 125

Bland-Hawthorn, J. & Jones, D. H. 1998, PASA, 15, 44

Boisson, C., Durret, F., Bergeron, J., & Petitjean, P. 1994, A&A, 285, 377

Boroson, T. A., Persson, S. E., & Oke, J. B. 1985, ApJ, 293, 120

Canizares, C. R., McClintock, J. E., & Ricker, G. R. 1978, ApJ, 226, L1

Carswell, R. F., Whelan, J. A. J., Smith, M. G, Boksenberg, A., & Tytler, D. 1982, MNRAS, 198, 91

Cooke, B. A., Rickets, M. J., Maccacaro, T., Pye, J. P., Elvis, M., Watson, M. G., Griffiths, R. E., Pounds, K. A., McHardy, I., Maccagni, D., Seward, F. D., Page, C. G., & Turner, M. J. L. 1978, MNRAS, 182, 489

Disney, M. J., Boyce, P. J., Blades, J. C., Boksenberg, A., Cane P., Deharveng, J. M., Macchetto, F., Mackay, C. D., Sparks, W. B., & Phillipps, S. 1995, Nature, 376, 150

Durret, F., Pécontal, E., Petitjean, P., & Bergeron, J. 1994, A&A, 291, 392

Fisher, K. B., Bahcall, J. N., Kirhakos, S., & Schneider, D. P. 1996, ApJ, 468, 469

Hansen, L., Nørgaard-Nielsen, H. U., & Jørgesen, H. E. 1984, A&A, 136, L11

Hutchings, J. B. & Campbell, B. 1983, Nature, 303, 584

Hutchings, J. B., Crampton, D., & Campbell, B. 1984, ApJ, 280, 41

Hutchings, J. B., Crampton, D., Campbell, B., Duncan, D., & Glendenning, B. 1984, ApJS, 55, 319

Hutchings, J. B., Crampton, D., Morris, S. L., Durand, D., & Steinbring, E. 1999, AJ, 117, 1109

Lim, J. & Ho, P. T. P. 1999, ApJ, 510, L7

Macchetto, F., Colina, L., Golombek, D., Perryman, M. A. C., & Alighieri, S. D. S. 1990, ApJ, 356, 389

McLure, R. J., Dunlop, J. S., Kukula, M. J., Baum, S. A., O'Dea, C. P., & Hughes, D. H. 1999, preprint astro-ph #9809030

Miller, J., Tran, H., & Sheinis, A. 1996, BAAS, 189, 2004

Mulder, P. S. & Valentijn, E. A. 1992, A&A, 259, 435

Murdoch, H. S., Hunstead, R. W., Pettini, M., & Blades, J. C. 1986, ApJ, 309, 19

Nørgaard-Nielsen, H. U., Hansen, L., Jørgesen, H. E., & Christensen, P. R. 1986, A&A, 169, 49

Osterbrock, D. E. 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (University Science Books: Mill Valley, California)

Phillips, M. M. 1980, ApJ, 236, L45

Ricker, G. R., Clarke, G. W., Doxsey, R. E., Dower, R. G., Jernigan, J. G., Delavaille, J. P., MacAlpine, G. M., & Hjellming, R. M. 1978, Nature, 271, 35

Stockton, A. & MacKenty, J. W. 1987, ApJ, 316, 584

Stone, R. P. S. & Baldwin, J. A. 1983, MNRAS, 204, 347

Urry, C. M., & Padovani, P. 1995, PASP, 107, 803

Véron-Cetty, M.-P. & Woltjer, L. 1990, A&A, 236, 69

This preprint was prepared with the AAS LaTeX macros v4.0.

Fig. 1.— Deep Hα images of the field surrounding the quasar MR 2251–178. Panels a and b are 1200 second exposures at redshifts of 0.0640 and 0.0645, respectively, panel c is an I-band continuum image of the same field, and panel d is a summed Hα image. A bright star (S), a nearby cluster galaxy (G1), and a number of emission-line knots from Macchetto *et al.* (1990) have been labeled. All panels are $3' \times 2.5'$ in size, with north up and east to the left. The lowest contour in panels a and b represents a surface brightness level of 1.2×10^{-17} erg s^{-1} cm^{-2} arcsec^{-2}, while that of panel d corresponds to 1.8×10^{-17} erg s^{-1} cm^{-2} arcsec^{-2}.